Electrical Properties II

Breakdown Fields along Various Crystal Orientations in 4H-, 6H-, and 3C-SiC

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A Comparative Study of the Electrical Properties of 4H-SiC Epilayers with Continuous and Dissociated Micropipes

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Analysis of High Leakage Currents in 4H-SiC Schottky Barrier Diodes Using Optical Beam Induced Current Measurements

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Electrical Activity of Residual Boron in Silicon Carbide

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P-3C-SiC/n-6H-SiC Heterojunctions: Structural and Electrical Characterization

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Breakdown Fields along Various Crystal Orientations in 4H-, 6H-, and 3C-SiC

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To design power devices, breakdown field is one of the most important material parameters. For 6H- and 4H-SiC along the $\langle 0001 \rangle$ direction, the breakdown fields [1, 2] as well as the impact ionization coefficients [3, 4] of electrons and holes have been measured, and it was found that holes primarily involve in avalanche multiplication. The breakdown field is also known to have anisotropy: in 6H-SiC the breakdown field along the $\langle 11\bar{2}0 \rangle$ direction is approximately two thirds of that along the $\langle 0001 \rangle$ direction [5]. However, the anisotropy of breakdown field in 4H-SiC has not been reported. In this study, the breakdown fields along various crystal orientations in 4H-SiC were measured. In addition, the breakdown fields along the $\langle 001 \rangle$ direction in 3C-SiC and its corresponding directions in 4H- and 6H-SiC were also investigated.

To measure the breakdown field, epitaxial p^+n diodes were fabricated. Employing mesa structure, we can assume parallel-plane breakdown if the depletion region does not reach the bottom of mesa. The substrates used in this study were 4H-SiC (0001) with 8° off-axis toward $\langle 11\bar{2}0 \rangle$ and 4H-SiC $(11\bar{2}0)$ from Cree Research, Inc., 6H-SiC $(0\bar{1}1\bar{4})$ and 4H-SiC $(03\bar{3}8)$ from SiXON Ltd., and high-quality 3C-SiC (001) grown on undulated Si from HOYA corporation [6]. 6H-SiC $(0\bar{1}1\bar{4})$ and 4H-SiC $(03\bar{3}8)$ are semi-equivalent to 3C-SiC (001) in the sense that these faces are inclined by 54.7° toward $\langle 01\bar{1}0 \rangle$ from $(000\bar{1})$ and (0001), respectively. The epilayers were grown simultaneously in a horizontal cold-wall CVD reactor using SiH_4 and C_3H_8 as source gases and H_2 as a carrier gas. Nitrogen and trimethylaluminum were used as doping sources for n- and p^+-layers, respectively. The doping concentration and the height of mesa were designed for 4H-SiC (0001). In general, more nitrogen atoms are incorporated into other faces than (0001), which reduces the width of the depletion regions, leading to more accurate measurements.

Figure 1 shows typical *I-V* characteristics of the diodes fabricated on 4H-SiC $(11\bar{2}0)$ and $(03\bar{3}8)$ measured at room and elevated temperatures. The breakdown voltage clearly increases with increasing temperature, suggesting avalanche breakdown. The diodes fabricated on 6H-SiC $(0\bar{1}1\bar{4})$ showed similar tendency.

Figure 2 shows the breakdown fields calculated from the avalanche breakdown voltages at room temperature, together with the breakdown field in a literature [3]. The breakdown fields along 4H-SiC $\langle 11\bar{2}0 \rangle$ and 4H-SiC $\langle 03\bar{3}8 \rangle$ were found to be about 75% of that along 4H-SiC $\langle 0001 \rangle$. For 3C-SiC, the breakdown field along $\langle 001 \rangle$ should be at least the preliminary value found in Fig. 2 for the thickness of about 10 μm, but might be somewhat higher, since the yield of the diodes fabricated on 3C-SiC was much lower than those on other polytypes.

The authors would like to thank SiXON Ltd. for supplying 6H-SiC $(0\bar{1}1\bar{4})$ and 4H-SiC $(03\bar{3}8)$ substrates. The authors are grateful to HOYA corporation for providing high-quality 3C-SiC (001) substrates.

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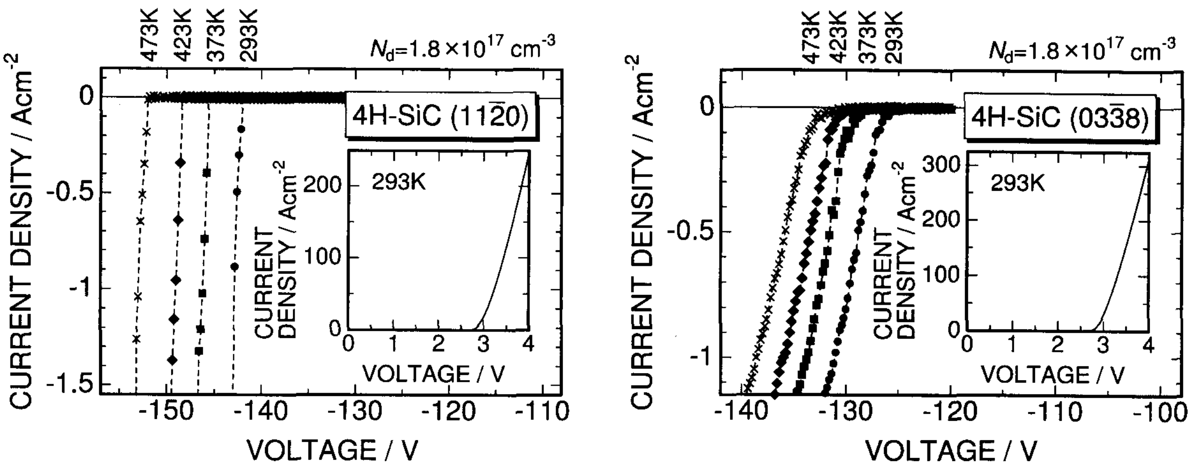

Figure 1: Typical reverse *I*-*V* characteristics of diodes fabricated on 4H-SiC (11$\bar{2}$0) and (03$\bar{3}$8) measured at room and elevated temperatures. Insets show forward *I*-*V* characteristics of the diodes measured at room temperature.

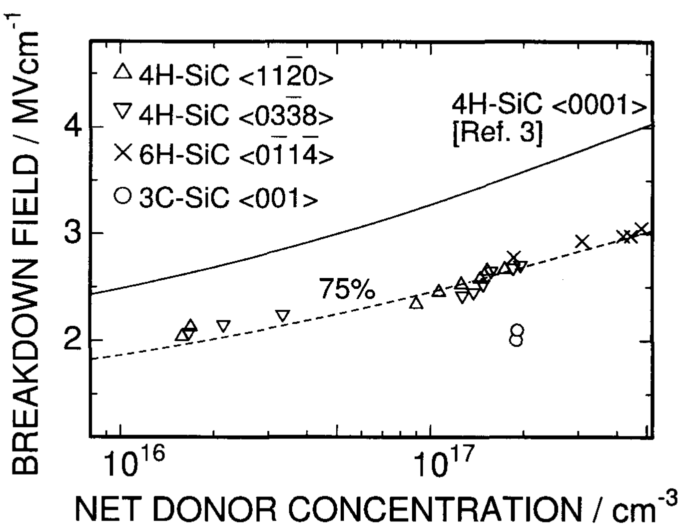

Figure 2: Breakdown field along various crystal orientations in three SiC polytypes at room temperature. The curve marked as 75 % denotes 75 % of the breakdown voltage along the ⟨0001⟩ direction in 4H-SiC suggested in Ref. 3.

A comparative study of the electrical properties of 4H-SiC epilayers with continuous and dissociated micropipes

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Micropipe is the most serious defect in SiC crystal which is included in 10^1 to 10^2 /cm^2 in commercial wafers, and it is well known that a micropipe in a substrate propagates into the epilayer by epitaxial growth. Its harmful features resulting from the early breakdown of pn diode and Schottky diode were reported. [1,2] Therefore, aiming at developing large capacity devices with high yield, It is necessary to decrease micropipe density.

Recently, we confirmed that some micropipes dissociated into several closed core screw dislocations through CVD growth. [3] In that study, KOH selective defect etching was applied for crystallographical evaluation. Continuous micropipe indicated large hexagonal etch pit with dark contrast, whereas dissociated micropipe showed several small assembled or aligned etch pits that were round in shape, which attributed to closed core screw dislocations dissociated from a micropipe. The probability of micropipe dissociation reached as high as 78% in the best result for an area of over 80mm^2.

With regard to vertical device application, a continuous hollow tube across the depression layer was closed by epigrowth; i.e. the SiC filled the entire depression layer instead of tubal air portion. Accordingly, an improvement of the electrical properties of the diode was expected as a result of the micropipe dissociation, even though several non-hollow core dislocations were generated. For this purpose, the electrical properties of the diodes fabricated on the epilayer have been investigate in this study.

Ni- Schottky barrier diodes in 0.5μm diameter with no edge termination were fabricated on 4H-SiC epilayer. The 21μm-thick epilayer was obtained using the radiant heating reactor with a growth rate as high as about 14μm/h. [4] Doping type and concentrations were determined as n-type ~5×10^{15}cm^{-3} by C-V characteristics. Nomarsky optical microscope observation and KOH etching were used for morphological and crystallographical study.

Continuous and dissociated micropipes accompanied by a linear depression along a $[11\bar{2}0]$ step-flow direction were visible on the epilayer surface. Therefore, the presence or absence of micropipes within the device area was recognized by the Nomarsky optical microscope. Micropipe dissociation and penetration was also checked using the KOH technique and transmission optical microscope observation after removing Ni contact.

I-V characteristics were investigated with reverse voltage up to -1000V. Fig. 1 and Fig. 2 show the I-V characteristics of the diodes including dissociated and continuous micropipe, respectively. Comparing electrical properties between dissociated and continuous micropipe, significant improvement of blocking performance was recognized for micropipe dissociation. The diode including dissociated micropipe blocked -1000V, whereas the diode involving continuous micropipe failed at or below -400V.

Morphological observation of the diode reached to the breakdown revealed that the breakdown current was passed through the micropipe, because the Ni contact was melted at the point on the micropipe.

The leakage current at -1000V of the diodes including dissociated micropipes ranged from 10^{-6} to 10^{-2} A/cm^2, whereas, the best-performing diode with no micropipe suppressed its leakage current as low as 10^{-6} A/cm^2. Wide differences in the leakage current were presented between the diodes with dissociated micropipes, which might have depended on the amount of non-hollow core dislocations, however further study on this is needed.

The maximum electrical field at the device surface fabricated on a net carrier concentration of ~5x10^{15} cm^{-3} and a 21μm-thick epilayer was calculated at reverse voltage -200V, -400V and -1000V as 0.6, 0.85 and 1.33 MV/cm. Thus, the layer on dissociated micropipes sustained up to 1.33 MV/cm, whereas the epilayer of continuous micropipes failed below 0.85MV/cm. This attributed to the material-changing effect in the depression area from air in the tubal defect to the SiC in the closed core dislocations.

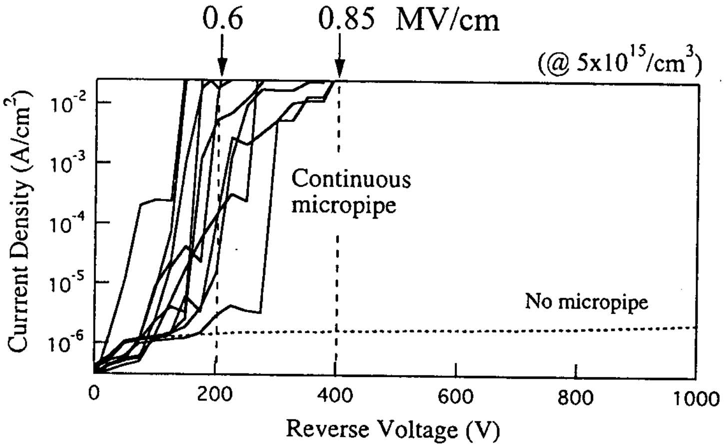

Fig. 1 I-V characteristics of diodes including continuous micropipe

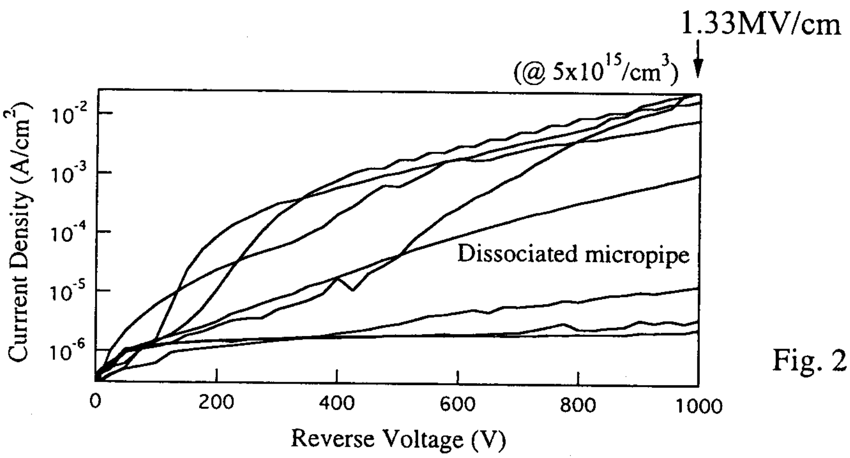

Fig. 2 I-V characteristics of diodes including dissociated micropipe

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Analysis of High Leakage Currents in 4H-SiC Schottky Barrier Diodes using Optical Beam Induced Current Measurements

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SiC Schottky barrier diodes (SiC-SBDs) have been expected to replace Si pin diodes by utilizing their properties with very low reverse recovery currents and high blocking voltages identical to Si pin diodes. However, there are several unsolved problems to show the great advantages against Si pin diodes. One of the challenges is to fabricate reproducible SBDs with low leakage currents especially in SBDs with large areas.

We have reported that these highly leaked SBDs include bright spots of optical beam induced current (OBIC) at the Schottky interfaces [1]. In this paper, we observed the cross sections under the bright spots of OBIC using cross sectional transmission electron microscopy (TEM) to clarify the origin of the bright spots. The dark regions due to the strain of the 4H-SiC crystal could be seen only under the bright spot of OBIC. These strains might be the cause of the high density of the deep levels, which could be the bright spots.

N-type 4H-SiC wafers, in which the c axis tilts 8 degrees to (11-20) direction, were purchased from Cree Research Inc. Epitaxial layers with the doping concentration of $10^{15}cm^{-3}$ were grown on (0001) Si face by hot wall LPCVD system [2]. After the implantation of guard rings, backside Ohmic contacts were formed with patterned windows, which correspond to the areas of Schottky contact. Schottky contacts were formed by sputtering of nickel and following annealing.

After the measurements of current-voltage characteristics of SBDs, OBIC measurements on the Schottky contacts were carried out from the polished backside of the wafer. The system is equipped with a He-Ne laser with a wavelength of 632.8nm (1.96eV). Since the energy is lower than the band gap of 4H-SiC, the laser can only excite carriers captured by the deep levels in the band gap. After putting marks by focused ion beam (FIB) close to the bright spots of OBIC, the sidewalls of the wafer were etched by FIB to observe the crystallinity under the Schottky interfaces using cross sectional TEM.

OBIC images at the Schottky interfaces are shown in figure 1 in thecase of high and low leakage currents. Bright spots could be observed at the Schottky contact with high leakage current as shown in figure 1(a). To the contrary, no bright spots appeared on the Schottky interface with low leakage current as shown in figure 1(b). A cross sectional TEM image, which includes the bright spot of OBIC pointed in figure 1(a), is shown in figure 2(a) with a normal region of TEM image for reference in figure 2(b). The dark regions with the size of 0.2 - 0.3μm, which are due to the crystal strains, could be observed under the Schottky interface. It can also be recognized that the thickness of the nickel film is not uniform over the distance of morethan 10μm around the bright spot of OBIC. These results might be the origin of the bright spots of OBIC. Further investigation will be presented on the view of step bunching and the fabrication process.

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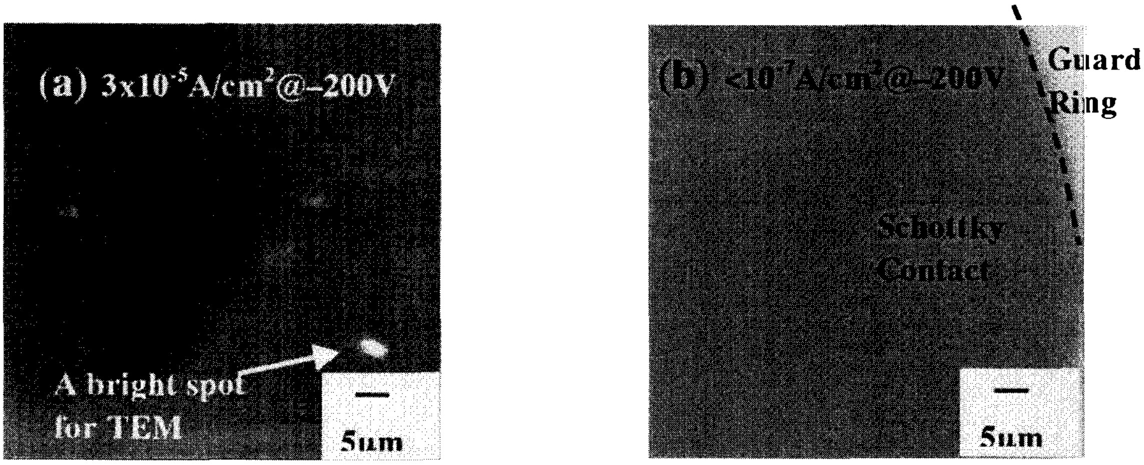

Figure 1 OBIC images at the Schottky interface in the case of high leakage current (a) and low leakage current (b)

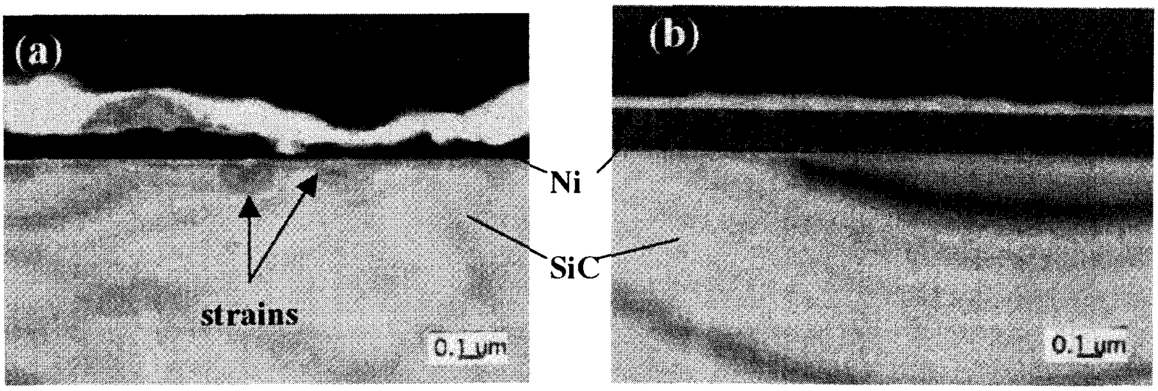

Figure 2 Cross Sectional TEM images under the bright spot of OBIC (a) and under the area without bright spots of OBIC for reference (b)

Electrical activity of residual boron in silicon carbide

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Control of residual boron in silicon carbide is an important issue when growing low doped crystals. However, the electrical properties of this common acceptor and its influence on material properties are little known. This is most probably due to the fact that sensitive electrical measurement techniques such as deep level transient spectroscopy (DLTS) are often limited to majority carrier traps and can not detect residual acceptor impurities in n-type material. DLTS measurements of p-type SiC are difficult to perform due to low temperature freeze-out of deep acceptors. In this work we have used minority carrier transient spectroscopy (MCTS) to avoid above mentioned complications. This technique does not require a *pn* junction in order to inject holes into depletion region, but uses above-bandgap illumination to create electron-hole pairs. A Schottky contact can then be used for the capacitance transient measurements.

We present a study of the boron acceptor in n-type CVD grown 4H silicon carbide. Using MCTS we were able to detect the presence of both shallow and deep boron (so called D-center) in the samples with the activation energies of 0.27 eV and 0.62 eV respectively (Fig.1). Effective capture cross-sections for holes obtained from the Arrhenius plot are $1.4 \cdot 10^{-13}$ and $9 \cdot 10^{-14}$ cm^2, respectively. By filling the traps with holes optically and then applying DLTS filling pulses, no noticeable decrease of the MCTS peaks amplitude was observed. This suggests that electron capture is inefficient, and that both defects act as very efficient hole trapping centers with large capture cross-section. From the capture cross-sections we estimate that even a low concentration in the order of $5 \cdot 10^{12}$ - 10^{13} cm^{-3} would limit the minority carrier lifetime to the level of 40 ns. This has also been confirmed experimentally where we have measured the boron concentration on different parts of a wafer with measured optical decay times ranging from 200 to 500 ns (Fig.1). These measurements were performed at relatively high injection, where some saturation of the trapping

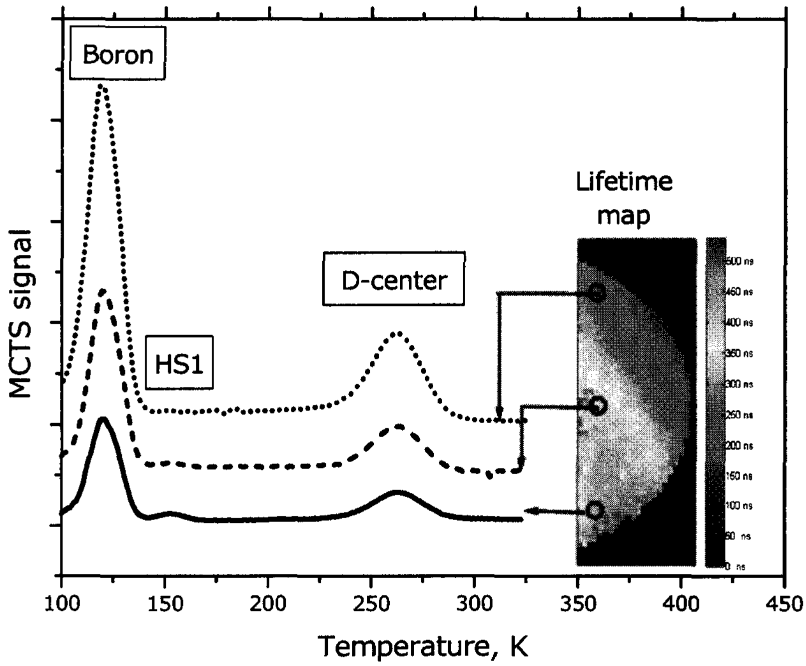

Fig. 1. MCTS spectra on wafer parts with different minority carrier lifetime

defects could be possible. The effect on low injection lifetime should be more pronounced. Optical decay measurements under different excitation conditions will be presented.

We have also performed a scanning-MCTS experiment by focusing the laser beam on different spots of a large Schottky contact. We were able to map the boron peak in different selected directions across the samples and compare with the data from minority carrier lifetime maps (Fig.2). We have found a clear correlation between the intensity of the boron signal and reduction of the minority carrier lifetime. Concentrations of other defects ($Z_{1/2}$, HS1) do not change remarkably in the low and high lifetime regions. Some reduction of the $Z_{1/2}$ peak was observed in the high-boron regions. This strongly indicates that the presence of boron is responsible for the observed lateral variation of minority carrier lifetime in high-quality silicon carbide.

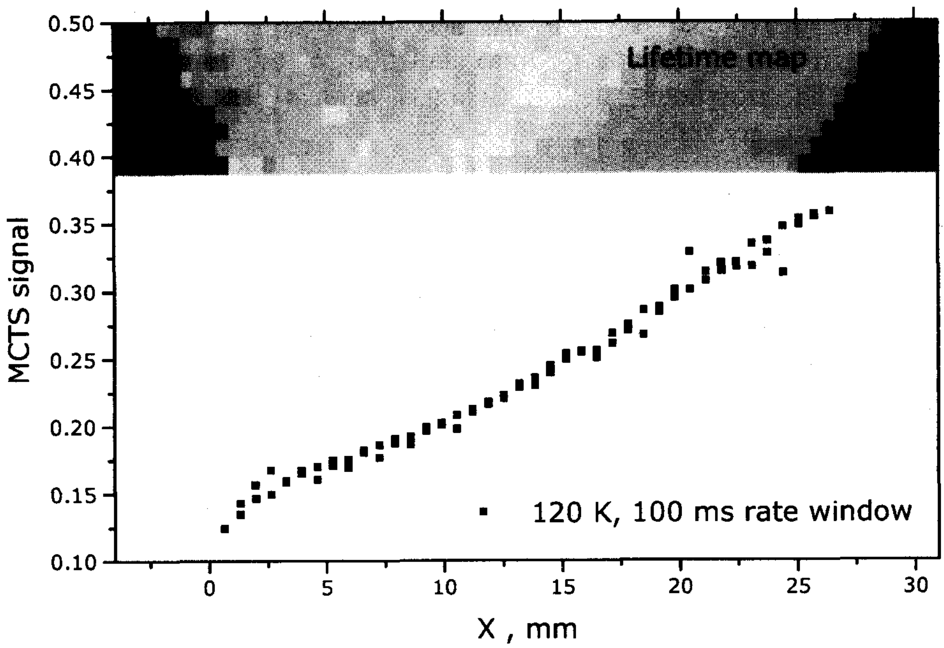

Fig. 2. Scanning MCTS at 120 K shows clear correlation between the intensity of the boron signal and reduction of the minority carrier lifetime

Mapping of the luminescence decay of low-doped n-4H-SiC at room-temperature

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For bipolar SiC power devices the lifetime of the carriers is a very important parameter (for a 5 kV p-n-diode a lifetime of approximately 400 ns should be reached). In order to control the decay time by a non-destructive method we use the time-resolved-photoluminescence (TRPL) at room-temperature to characterize low n-doped 4H-SiC epitaxial layers concerning the decay time and the homogeneity over the entire area.
The main part of the excited carriers recombines radiationless. Therefore the measured small fraction of radiative transitions is used to monitor the whole time behaviour of the recombination process.

For this we move the sample using a steppingmotor driven x-y-table to draw up a mapping of the luminescence decay after excitation with a short laser pulse. The experimental setup is shown in Fig. 1.

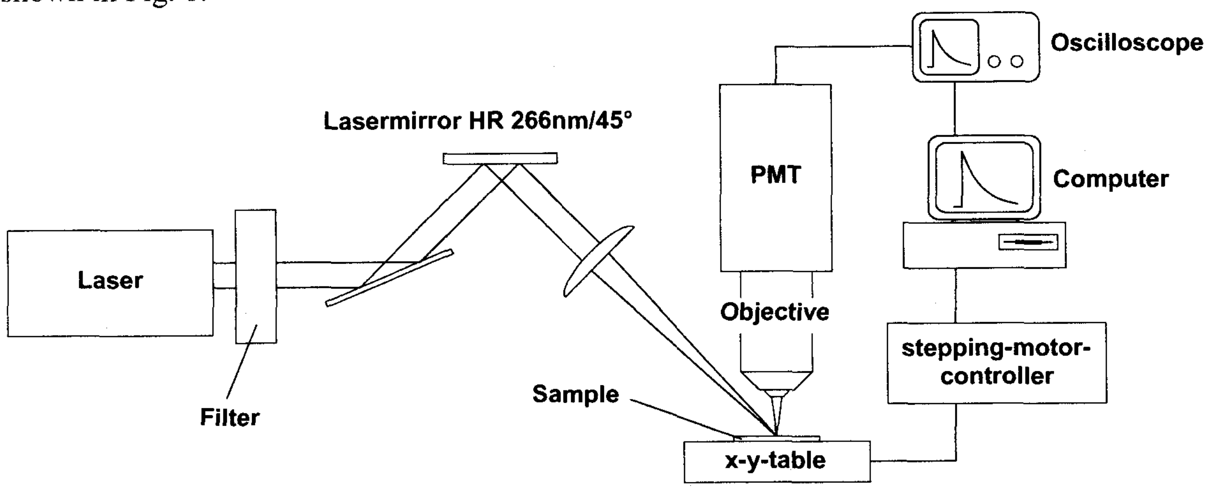

Fig. 1: Experimental setup of the TRPL

The excitation source is a frequency quadrupled pulsed Nd:YAG laser with a maximum repetition rate of 30 Hz, a pulse width of 4 ns (FWHM) and a wavelength of 266 nm. The penetration depth in 4H-SiC at room-temperature for this wavelength is about 0.5 µm [1]. The spot on the sample has a size of 10x15 µm so that also small structures can be measured.
Unlike most investigations using the TRPL-method [2] we use no spectral selection of single wavelengths of the PL-light. All the emitted light is collected by a quartz objective to a photomultiplier and the signal is recorded by a digital oscilloscope averaging over 150 pulses. Fig. 2 shows a typical signal.
Due to the time response of the photomultiplier we are limited to decay-times longer then 20 ns.

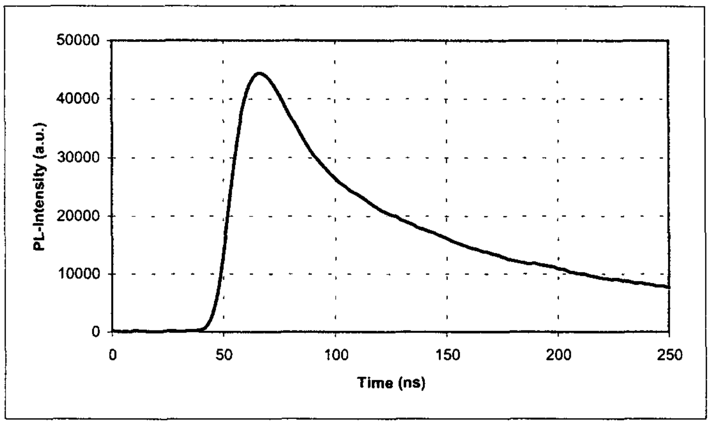

Fig 2: Typical luminescence decay signal ($\tau = 112$ ns)

Epilayer:
thickness 40 µm,
doping 5.09 $10^{14}cm^{-3}$

In this abstract, we demonstrate first results of the time resolved photoluminescence on 4H-SiC. Substrates and low-n-doped epilayers have been measured.
The main features are:
- big differences concerning homogeneity and decay-constants can be observed,
- decay times mostly are in the range of 60 to 150 ns for epilayers and
- decay times up to 535 ns averaged over the measured area could be observed on single samples (Fig. 3).

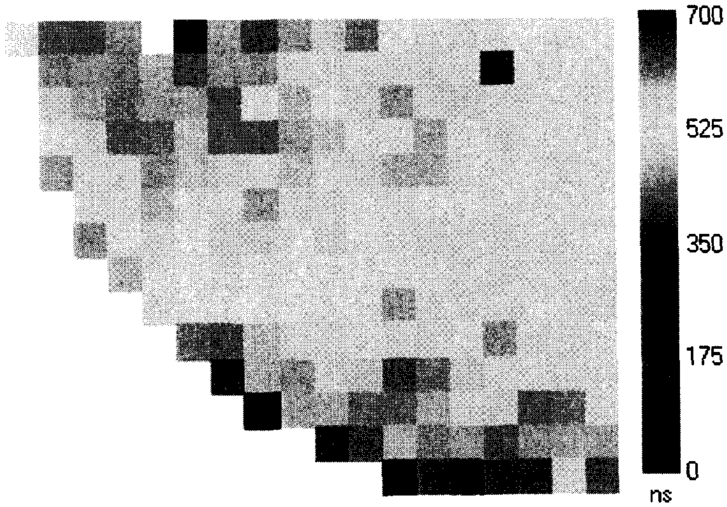

Fig 3: Mapping of the decay times (after 200 ns of the excitation pulse) of a part of a 4H-SiC epilayer from CREE

Epilayer:
thickness 50 µm,
doping 7.5 $10^{14}cm^{-3}$

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P-3C-SIC/N-6H-SIC HETEROJUNCTIONS: STRUCTURAL AND ELECTRICAL CHARACTERIZATION .

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The presence of a large number of crystalline modifications (polytypes), which have identical composition but may markedly differ in electrical properties, makes SiC a promising material for creating various heterostructures. Progress in the sublimation epitaxy in vacuum technology enabled fabrication of n-3C-SiC/n-6H-SiC epitaxial heterostructures with good quality of the 3C-SiC epilayer [1]. Aim of the present study is growth and and investigation heteropolytypes 3C-6H SiC pn structures.

Investigated p-n structures were grown by sublimation heteroepitaxy in vacuum on 6H-SiC (0001) Lely substrates. X-ray diffractometry confirm presents of SiC films of the both polytypes. An ohmic contact was formed on p-type region by deposition of Al and Ti and annealing at 1100°C. Mesa structures with an area $3x10^{-3}$ cm^2, 10^{-4} cm^2 and $8x10^{-5}$ cm^2 were formed by reactive ion-plasma etching using Al mask

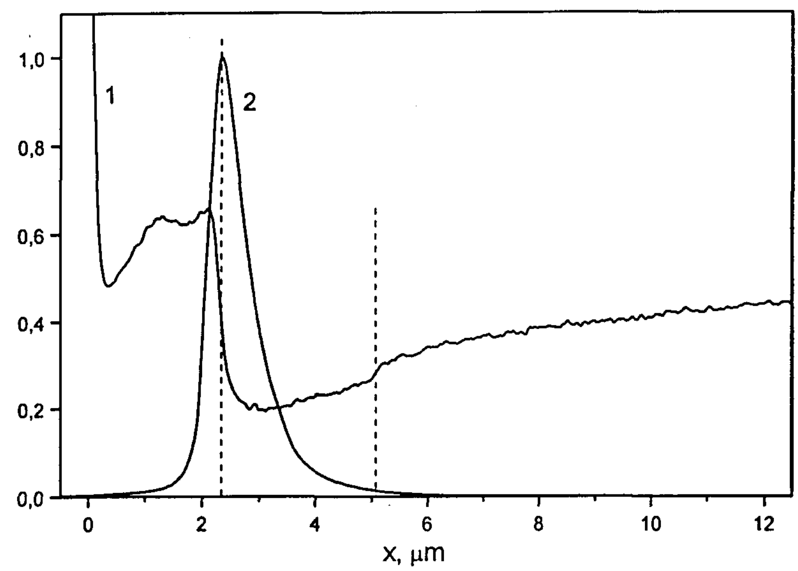

Fig.1. Line profiles of secondary electron (1) and EBIC (2) signals for investigated diodes.

The diode cross sections were studied by the methods of electron beam induced current (EBIC) and secondary electrons (SE) in a JSM-50A scanning electron microscope. In the SE mode, two regions with SE signal jump were observed (Fig. 1). One of these corresponds to the p-3C SiC--n- 6H SiC heterojunction, and the other, to n-6H SiC—n+ 6H-SiC substrate junction. In the given case, the SE signal jump was abrupt and exactly coincided in position with the peak in the EBIC curve, thereby indicating that the given p--n junction is abrupt. The investigations demonstrated that the p-regions of diodes is homogeneous.

C-V characteristics of the diode was linear in coordinate C^{-2}–U, which mean that obtained pn junction was abrupt. The concentration Nd-Na was 1-2x10^{17} cm^{-3} in n-type layers, and Na-Nd ~ 3 10^{18} cm^{-3} on the surface of the p-type region. Capacitance cut of voltage (U_c^c) was 2,65 ± 0,05 V for this diodes . It was shown, that at low current densities the dependence of the current on voltage is exponential: $J = J_0 \exp(qV/nkT)$. The ideality factor is about 2.1--2.4.

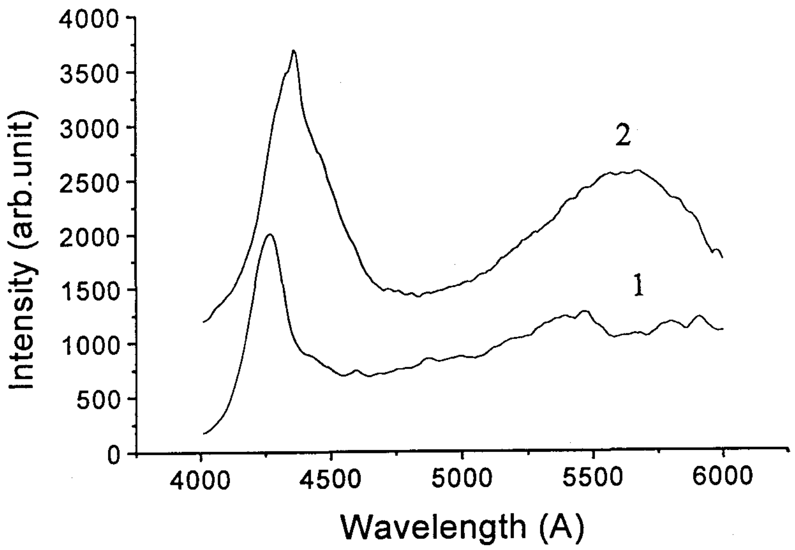

Fig.2 Electroluminescence spectra at forward current 70 mA, T = 300 K (1); 600 K (2) (curve 2 is shifted up on 1000 units)

Electroluminescence bands with $h\nu_{max} \approx 2.9$ eV and $h\nu_{max} \approx 2.3$ eV are observed simultaneously in the diodes in temperature range 300-600 K (fig.2). These EL bands in 3C-SiC and 6H-SiC are usually considered to be due to the free exciton annihilation.

The determined, from U_c^c value and Fermi level position, band discontinuities $\Delta Ec = 0.55 \pm 0,05$eV and $\Delta Ev = 0...0.05$ eV are in good agreement with theoretical calculations [2] and experimental electron affinity values for 6H and 3C SiC [3]. The low ΔEv value does not hinder hole injection from p+ 3C SiC into n-6H SiC. At the same time, injection of electrons from the wide bandgap material into that with narrow band gap is also possible. Thus, the EL spectrum of such a structure may contain emissions bands associated with recombination in both 6H and 3C SiC, which is the case in the experiment.

The estimated band structure confirm the possibility in principle of creating a field-effect transistor with 2D electron gas (HEMT), based on the 3C--6H SiC heterojunction.

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